CONDITION MONITORING OF NUCLEAR CABLES USING THE INDENTER MODULUS

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1 ABSTRACT

In general, the degradation of low voltage power, control and instrumentation cables is due to the oxidative embrittlement of the insulation and jacket materials. Experience has shown that service cable failure has occurred due to the embrittlement and cracking of the insulation followed by a loss of dielectric strength and high leakage currents. Consequently, the end of life criteria for insulation has been based on absolute elongation at break values. However, samples required to measure elongation values are relatively large and require the removal of cable sections from the plant. The Indenter Polymer Aging Monitor was developed for use as an in-situ, non-destructive diagnostic tool for tracking the degradation of nuclear cables and seals. The operation of the Indenter is discussed along with laboratory and field results.

2 BACKGROUND

Safety related power, control, and instrumentation cables are critical to the safe operation of nuclear power plants, and require environmental qualification [EQ] to provide assurance that common mode failure does not occur during service or during a design basis accident [DBA]. EQ test procedures use the environmental service conditions provided by the utility or plant designer to calculated the duration of accelerated thermal aging and radiation exposure. Postulated service conditions are often generalized to a given room or elevation and do not take into account local variations in stress conditions. Dose rate effects and synergistic effects may not be encompassed by EQ testing procedures. Therefore, due to the difficulty of predicting cable life, a great deal of effort by various research organizations is being expended in the development of in-situ condition monitoring techniques.

Experience has shown that the failure of nuclear cables is primarily due to the hardening and embrittlement of the insulation resulting in the formation of micro cracks, a loss of dielectric strength and high leakage currents. Micro cracks can occur in the embrittled insulation due to thermal expansion and contraction of the insulation, or the manipulation of the cable during maintenance. Consequently the end of life criteria for insulation can be either a percentage decrease of elongation from the as received value or an absolute elongation at break value. The trend by utilities is to specify an end of life as 50 % absolute elongation. This value will provide a sufficient margin for the insulation to function without decreasing electrical performance and pass a design basis event. There have been several reports and standards that have either stated the requirements for a 50 % absolute elongation criteria or have discussed the rationale for accepting this value.(1, 2, 3)

Monitoring cable degradation by measuring absolute elongation is in many cases not feasible as it requires the periodic removal of cable samples from the field for destructive testing. The Indenter Polymer Aging Monitor, known as "the Indenter" provides an in-situ, non-destructive technique for tracking service cable degradation. Indenter Modulus measurements, taken in the field, can be correlated to elongation values in the laboratory using accelerated aging techniques. Tracking insulation degradation will not only provide assurance of the viability of the cables at the time of measurement but can be used to justify the use of cables beyond the presently established qualified life. This is an important factor in the support of plant life extension and licence renewal considerations.

The Indenter has been used successfully in the USA to track cable materials such as, ethylene propylene rubber (EPR), chlorosulphonated polyethylene (CSPE) and neoprene rubber.(4) The Canadian nuclear cable design consists of cables with PVC jacket and either PVC, FREPR or FRXLPE insulation and this discussion will be focused on these materials.

3 INDENTER OPERATION

The Indenter was developed under the auspices of the Electric Power Research Institute (EPRI) in the USA and the first commercial unit was introduced in late 1990. The Indenter uses an anvil (probe) which is driven against the cable jacket or insulation at a constant speed during which the force and deformation depth into the material are measured to yield compressive modulus. The test is terminated and the probe is retracted when a pre-set force limit is reached. A conceptual diagram of the Indenter is provided in Figure 1.

The indenter test equipment assembly is a portable, self-contained device that is battery powered. The equipment consists of a cable clamping assembly, connecting cable, control box and a laptop computer. The clamping assembly can be changed to accommodate large size multi conductor cables as well as individual small size wires. Figure 2 provides details of the clamping assembly. The operation of the indenter is digitally controlled to allow different velocities and force limits to be used in the testing of materials with different hardness properties.

The software package provided with the Indenter allows the user to view the results after each measurement. Data can be displayed relating the force, velocity and displacement of the anvil during the test run. Figures 3 shows a typical force vs. displacement display, while Figure 4 shows the force vs. time display for the same measurement. The modulus is calculated by dividing the change in force by the displacement.

4 CABLE CONDITION MONITORING AT POINT LEPREAU

In 1995, PLGS initiated a cable aging monitoring program to provide a surveillance method to support the qualified life of safety-related cables, and a means of generally predicting the useful life of cables throughout the station in support of possible plant life extension efforts.

The program is intended to be implemented in the following phases:

Phase 1: Selection of a primary method of broadly sampling cables. (Completed 1995)

Phase 2: Select initial sample base and retrieve field data. (Completed 1995)

Phase 3: Baseline (fingerprint) the Indenter "modulus-to-elongation at break" correlation for the relevant cable types as well as indicators from supplementary monitoring methods (Scheduled 96/97)

Phase 4: Broaden the field cable sample base over time and implement a formalized system of regularly retrieving and analyzing data. (Long term)

It was recognized that phases 3 and 4 would demand a significant amount of time and effort to complete, however, it was felt that it was important to begin retrieving field data as early as possible to permit more accurate predictive analysis earlier in the life of the plant. In order to take advantage of a planned extended outage, phases 1 and 2 were undertaken immediately. These two phases are discussed in more detail below.

4.1 PHASE 1 - Selection of Primary Method of Cable Aging Monitoring

The EPRI Indenter was selected as the primary method of retrieving aging sensitive data due its following advantages:

- useful acceptance criteria are achievable
- non-destructive
- non-intrusive
- easily portable
- widely used in the nuclear power industry

4.2 PHASE 2 - Selection of Initial Sample Base and Retrieval of Data

4.2.1 Cable Selection Criteria

- Select generic types of power and control cables (i.e. FRPVC/FRPVC, FRPVC/FRPVC, FRPVC/PVC/PVC) that represent the largest volume of station cables, with emphasis on EQ cables.
- Cable type (SCN) must be positively identified in the field.
- Cable dimensions must be accommodated by indenter probe and sufficient slack must be available to provide adequate clearance to attach the clamp.
- Select cables known to have a significant continuous electrical loading, or frequent inrush transients.
- Select same and similar cables in different locations with different environments.
- Select similar cables in same location/environment.
- Select cables installed prior to commissioning.

4.2.2 Location Selection Criteria

- Confine selection to Reactor Building to maximize benefit of long outage and focus on EQ cables and worst perceived environment.
- Provide a broad cross-section of the R/B environment including radiation and thermal "hot spots".
- Include areas where there is a high concentration of cables.
- Locations must be accessible as much as possible (to minimize staging support).
- Select locations where abandoned cable is available to coupon for supplementary destructive testing.
- Identify secondary sample sites (e.g. Specific cable trays, conduits, JB entrances) with larger primary sites (e.g. North end of east transmitter room).

4.2.3 Cable Identification and Marking

Each selected cable is uniquely identified with an ID# which denotes the primary location, secondary location and serial number of the cable sample. For example, cable sample R6A4 would be located in primary site "R6" (R/B West F/M Vault, el. 45' + 20), at secondary site "A" (cabletray CP4015), cable sample #4. This identification systems permits easy sorting of data by locations. A general arrangement of relevant locations, with sample site locations clearly identified, is documented to enable quick location of the sites analysis and future field measurements.

Each cable sample area is marked with two laminated cable ID# tags, positioned 1 to 2 feet apart between which indenter measurements are to be taken. This sample zone permits multiple sample points on a single cable while ensuring that future sampling is confined the same small defined area.

4.2.4 Database Development

A relational database was developed to record cable sample description and location information. This database was first used to provide a form to use as a guide and checklist for performing field measurements, as well as a means for recording problems or other relevant feedback. Data retrieved via the indenter software will be transferred to the PLGS Cable Aging Monitoring Database for long term tracking and trending analysis.

4.2.5 Preparation for Field Measurements

All staging, ladders, safety harnesses, etc, were available and in place and shop support was reserved. A key factor in minimizing effort to prepare for and execute field indenter measurement was the early involvement of Operations.

Many of the field cables selected for sampling carry special safety and safety related systems circuits. Many more cables are "black snakes" located in the middle of main cableway trunks where the end devices are not easily determined. In the early stages of phase 2 a presentation was given to senior Operations personnel demonstrating the non-intrusive nature and safety features of the indenter. This avoided the need to incorporate workplans and post maintenance testing into the field work. This also facilitated quick approval of work permits. It may be prudent, however, to ensure the indenter and a sample of cable is nearby when requesting a work permit in the event that an individual shift supervisor requires further convincing.

4.3 Experience Gained

- Relaxation modulus used to sample XLPE insulation was ineffective due to mechanical noise induced by vibration from operating machinery. The possibility of providing filtering is being investigated.
- The probe clamping arrangement can be improved to provide more consistent grip on cables. The present arrangement is of limited use at cable bends.
- Cable sampling areas should be cleaned prior to taking measurements to prevent interference from surface contaminants.
- The Indenter provides a convenient and effective method of retrieving cable age trending data from a broad population of field samples.

5 INDENTER DATABASE DEVELOPMENT AT MEC

Cables jacketed with PVC were irradiated and thermally aged to simulate field service of up to 50 years and elongation and Indenter modulus recorded for both the jacket and insulation materials. The results show the relationship between elongation and modulus values.

5.1 Objectives of the Research Program

- Develop an aging database using the Indenter for commonly used nuclear materials.
- Determine the factors that will improve the sensitivity of the modulus indenter to measure nuclear cable embrittlement.

5.2 Cable Design

The three cable designs used for the evaluation were supplied by two Canadian cable manufacturers. The cable designs are typical of the cables used at Canadian nuclear power plants. Although all the jacket materials were polyvinyl chloride [PVC], the formulations of the PVC jackets were different. The insulations were ethylene propylene rubber [EPR], crosslinked polyethylene [XLPE] and PVC. A description of cable designs is given in Table 1.

For each cable design, six 300 mm cable lengths were prepared. One length was used for the indenter modulus evaluations and the rest of the cable sections were prepared for elongation measurements. The jacket on cable samples to be used for Indenter modulus was slit length wise for a length of 100 mm to allow access to the individual conductors. During aging, the jacket section was held in place by a copper wire. The cable sections for elongation measurements were disassembled by cutting and stripping off the jacket. The copper conductors were removed from 10 of the individual wires and the ends of the resulting tubes sealed with RTV Silicone. This was necessary due to the difficulty in removing the wires after thermal aging for elongation measurements of the insulation.. All the components of the cable were then assembled and the jacket was held in place with wrapped copper wires, simulating a field cable section.

5.3 Thermal Aging

The prepared cable sections were hung vertically in an air forced heated oven and kept at 130°C for periods to represent service life at 55°C for approximately 20, 30, 40 and 50 years. The aging periods were calculated using the Arrhenius equation with an activation energy of 1.0 eV.

The Equation used was:

$$k = A \exp(-[E_a / k_B T]) \qquad (1)$$

where:

- k = reaction rate
- A = frequency factor
- exp = exponent to base e
- E_a = activation energy
- k_B = Boltzmann's Constant
- T = absolute temperature (Kelvin)

Life is assumed to be inversely proportional to the chemical reaction rate. In terms of life, and after converting to Napierian base logarithms, Equation (1) becomes:

$$\ln(\text{life}) = (E_a / k_B)\, 1/T + \text{Constant} \qquad (2)$$

Using the Arrhenius equation, the time required to simulate thermal aging during service is presented in Table 2.

5.4 Radiation and Thermal Aging

Cable sections similar to that of the thermal aging study were prepared and submitted to the Isomedix Corporation for irradiation. The samples were irradiated using Cobalt 60 to a total dose ranging from 294 kGy to 326 kGy [29.4 Mrad to 32.6 Mrad] at a dose rate of 0.81 kGy/h to 2.53 kGy/h. After irradiation elongation and Indenter modulus results were obtained. The irradiated samples were then thermally aged to simulate field aging.

5.5 Material Evaluation

5.5.1 Elongation

Two types of specimens were prepared for elongation evaluation. For the PVC jackets, micro die specimens, as per ASTM D638 Die No 5 were used, while for the insulation tubular specimens prepared as per CSA C22.2 No 0.3 Clause 4.3.1 were used. The pulling speed for all specimens was 8.5 mm / s.

5.5.2 Indenter Modulus

Indenter modulus was measured for both the jacket and insulation. For each test set a total of ten (10) measurements were taken. For all measurements, the software parameters controlling the operation of the Indenter were set as follows:

Desired Velocity:	12.7 mm/min
High Force Limit:	15.0 Newtons
Maximum Force Allowed:	20.0 Newtons
Maximum Deformation:	1.00 mm
Maximum Travel:	7.00 mm
Modulus Low Force:	2.00 Newtons
Modulus High Force:	14.0 Newtons

5.6 Test Results

5.6.1 Thermal Aging

Both the Indenter modulus and elongation initial values, as listed in Table 3, confirm that the three PVC jacket materials were different. The aging rates also differed, with the elongation value decreasing 6 % for cable jacket NRC1, 21 % and 24 % for NRC2 and NRC3 respectively after an equivalent 20 years of aging. Although all three PVC jackets showed a decrease in elongation values and an increase in Indenter modulus, the materials exhibited relatively good resistance towards thermal aging and remained flexible even after a simulated 50 year service life. The percent elongation decreased from 54 % to 46 % from the as received values. For the same aging period, the indenter modulus increased by 23 % to 50 %.

For the insulation systems, the Indenter modulus was less successful in tracking aging of the XLPE and EPR materials. The lack of change in modulus for EPR can be explained by the fact that the elongation showed only a minimal change (9 % decrease) after a simulated 50 year aging. The exceptional aging resistance of the EPR was confirmed by both the elongation and modulus values. A surprising aspect of this study was the poor thermal stability of this particular XLPE. The elongation value decreased from 274 % elongation to 65 %, a decrease of 76 % after the same aging period as the EPR.

5.6.2 Radiation and Thermal Aging

The cable samples were irradiated to an average level of approximately 310 kGy [31 Mrad] which would for some plants represent 40 years of service. It can be seen from the results in Table 4 that radiation had a more significant effect than thermal aging. This was especially noticeable for the PVC materials where the elongation values after an equivalent 10 years of service life decreased by 67% to 75% while thermally aged only samples decreased by less than 50% after an equivalent service aging of 50 years. For the insulations the elongation values decreased from the mid two hundred percent to the one hundred percent range, a decrease of 61% to 67%. The indenter modulus for EPR and XLPE increased by 17% indicating a hardening of the materials on irradiation.

It is known that PVC undergoes chain scission creating low molecular components during irradiation and it would be expected that the material would become softer. This is what in fact the indenter modulus indicated. The modulus values decreased after radiation. However,with thermal aging the modulus values increased as the low molecular components diffused from the compound, and the material became harder.

5.6.3 Indenter Modulus Correlation to Elongation for PVC/PVC Cable

During field use, the cable insulation is not accessible for measurement using the Indenter. For this reason, modulus measurements taken on the cable jacket must be correlated to the physical condition of the insulation. Figure 5 provides a plot of Indenter modulus and % elongation for the PVC insulation during thermal aging. In Figure 6 the Indenter modulus of the PVC jacket along with % elongation of the PVC insulation are plotted against thermal aging duration. The reduction in % elongation of the insulation is closely tracked by the increase in modulus of the jacket. Figure 7 shows the Indenter modulus and % elongation for the PVC insulation after irradiation plotted against thermal aging duration. The absolute elongation of the irradiated PVC insulation is less 50% at 10 years equivalent thermal aging. Figure 8 shows the relationship between % elongation of the PVC insulation and the Indenter modulus of the jacket for the irradiated samples during thermal aging.

5.7 Conclusions and Recommendations

- Thermal aging of PVC jackets, PVC and EPR insulations can be tracked using the modulus indenter. For the nuclear cable materials the modulus measurements relate to elongation values.

- The indenter modulus measurements were less successful in tracking the embrittlement of XLPE. However, by establishing the aging relationship between the PVC jacket and the XLPE insulation the degradation of XLPE can be predicted.

- The combination of irradiation followed by thermal aging increases the aging rate of all the materials, but especially that of PVC when compared with only thermal aging. Both the indenter modulus and elongation measurements can track the increased rate of aging.

- It is recommended that the anvil or probe be modified to improve the capability of the device to track the aging of hard materials such as XLPE.

6 REFERENCES

1. H. Danielsson, H. Schonbacher and M. Talvet. Estimate of Lifetime of Cables in the Radiation Environment of LEP 200. Presented at the IAEA Consultants Meeting on Radiation Degradation in Polymers. Maryland USA, July 1991.

2. Shielded, Nuclear Grade, Control Cable - 300 V, for use in Generating Stations. Ontario Hydro Standard Specification M - 592-SM-81, 1981.

3. W. Michel, Prognosis on the Aging of Cables. IAEA Specialists Meeting on Effectiveness of Methods for Detection and Monitoring of Age Related Degradation in Nuclear Power Plants, Bariloche, Argentina, October 17-19, 1995.

4. G. J. Toman, R.F. Gazdzinski. "Results of indenter testing of in-plant and artificially aged cable specimens". IEEE International Symposium on Electrical Insulation, June 5-8, 1994.

Cable Sample	Insulation	Jacket	Voltage V	Conductor Size AWG	No. of Conductors	Copper Shielding
1	PVC	PVC	300	No. 16	7 pr.	yes
2	FRXLPE	PVC	300	No. 16	7 pr.	yes
3	EPR	PVC	600	No. 12	12	no

Table 1: Cable Descriptions

Aging Period (h) @ 130°C to Represent Years of Service Life @ 55°C For the Materials: FREPR FRXLPE PVC				
YEARS	20	30	40	50
HOURS	242	363	484	605

Table 2: Aging Periods Used to Simulate Field Service

Aged Equivalent	Baseline (0 h)		20 Years (242 h)		30 Years (363 h)		40 Years (484 h)		50 Years (605 h)	
Sample	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus
NRC1 EPR Insulation	275	29	263	27	259	25	255	26	251	25
PVC Jacket	432	21	408	20	356	23	318	23	283	26
NRC2 PVC Insulation	262	44	224	52	213	59	182	66	150	72
PVC Jacket	412	32	324	37	284	44	234	48	225	48
NRC3 XLPE Insulation	274	48	113	49	90	48	90	51	65	49
PVC Jacket	388	34	294	36	204	45	204	44	208	51

Table 3: Thermal Aging Results for % Elongation and Indenter Modulus

Sample	Unaged (As Recieved)		No Thermal Aging		Radiation 31 Mrad					
					10 Years (121 h)		20 Years (242 h)		30 Years (363 h)	
	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus	% Elongation	Indenter Modulus
NRC1 EPR Insulation	275	29	106	34	115	32	133	31	98	30
PVC Jacket	432	21	262	18	142	21	122	25	63	31
NRC2 PVC Insulation	262	44	91	37	36	76	29	94	10	96
PVC Jacket	412	32	188	33	102	40	80	49	28	63
NRC3 XLPE Insulation	274	48	91	56	118	50	86	45	95	42
PVC Jacket	388	34	156	29	102	40	84	47	32	64

Table 4: Radiation and Thermal Aging Results for % Elongation and Indenter Modulus

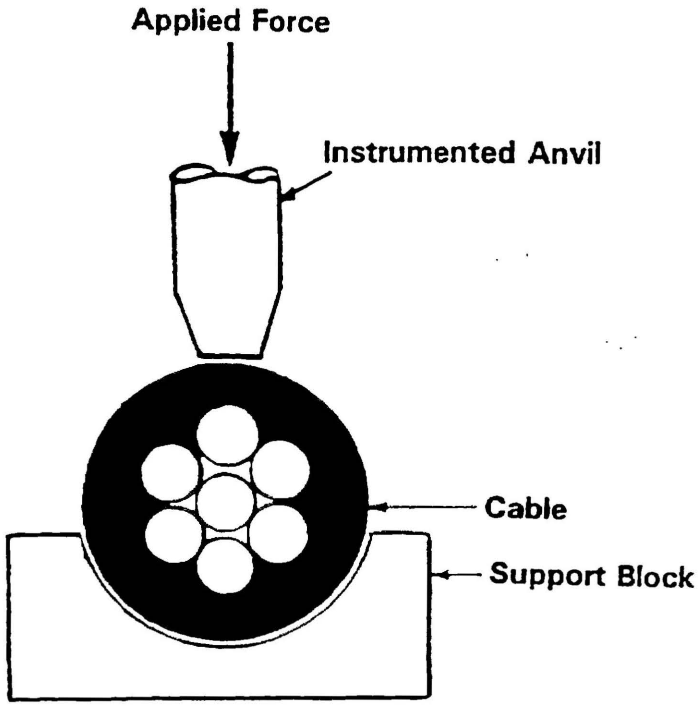

Figure 1: Indenter Conceptual Diagram

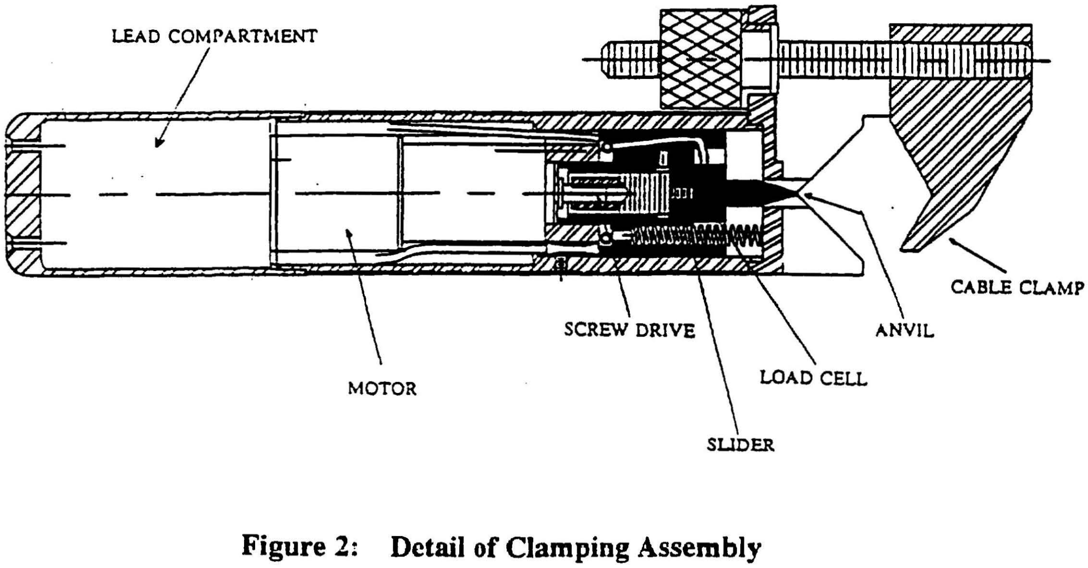

Figure 2: Detail of Clamping Assembly

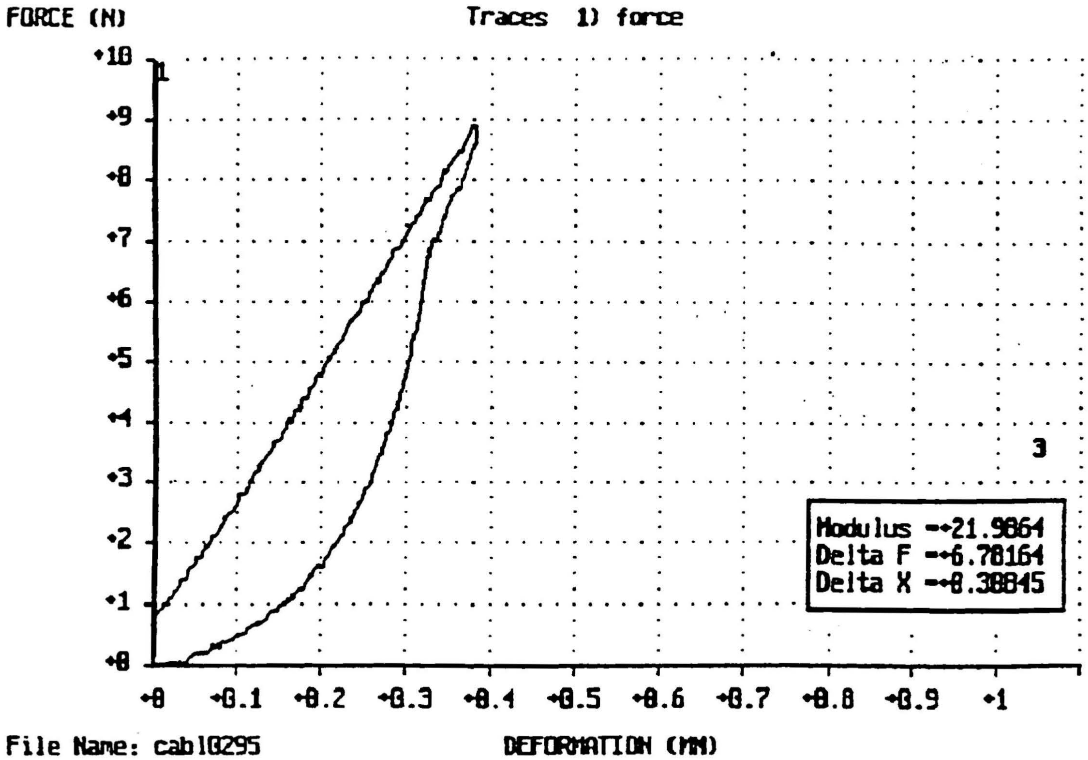

Figure 3: Typical Force vs. Displacement Plot

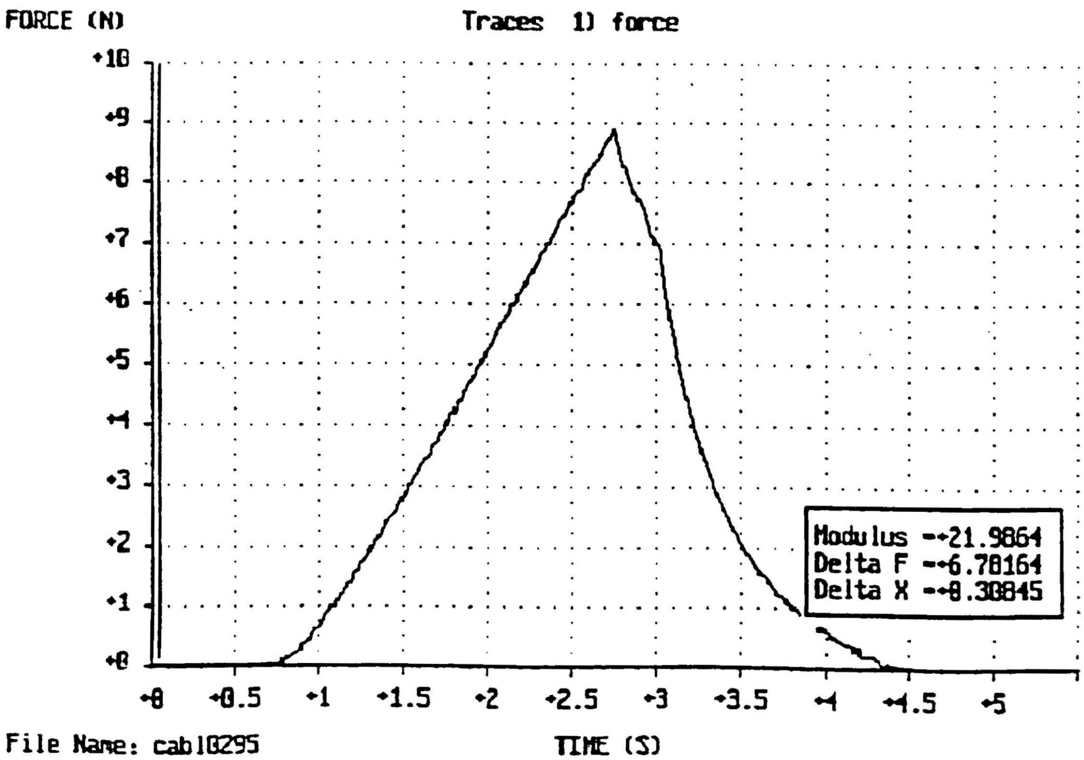

Figure 4: Typical Force vs. Time Plot

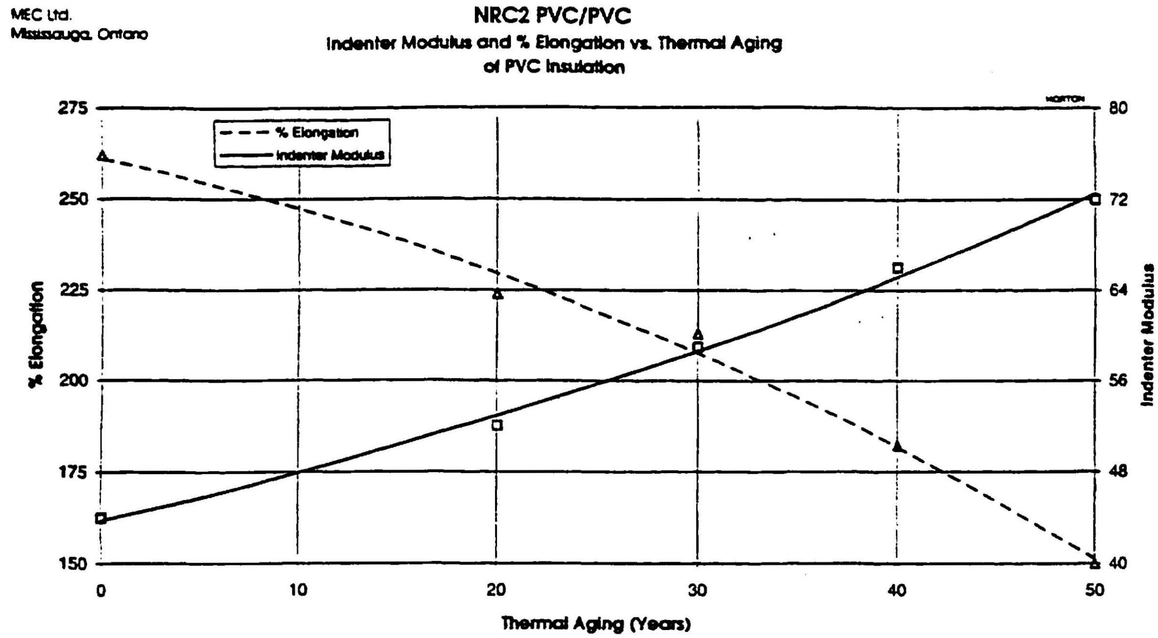

Figure 5

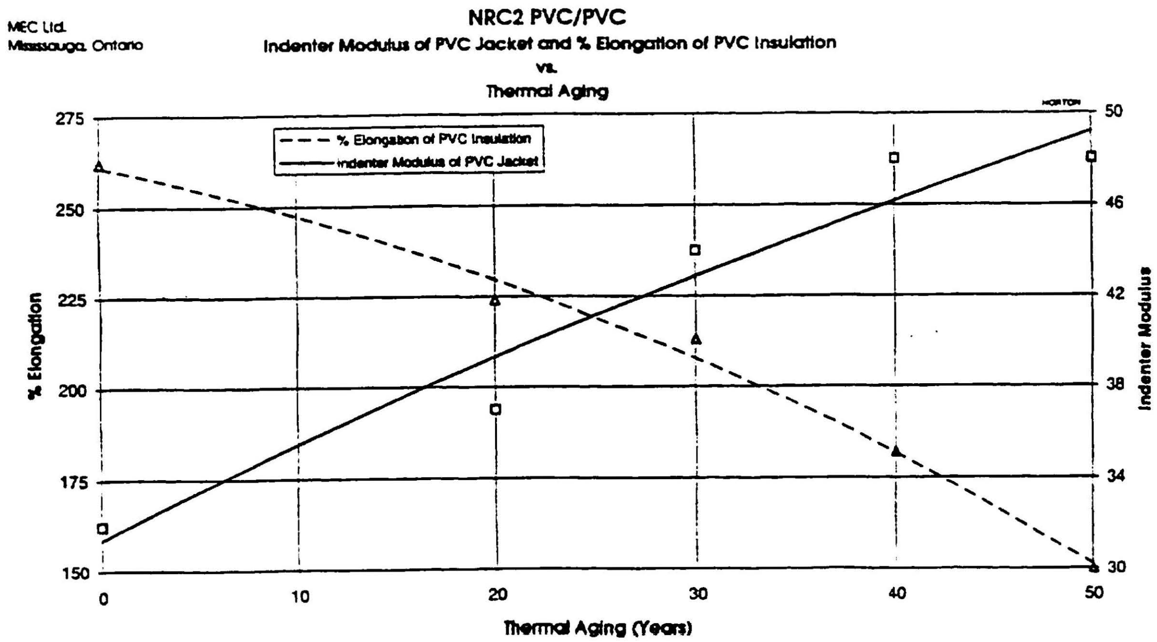

Figure 6

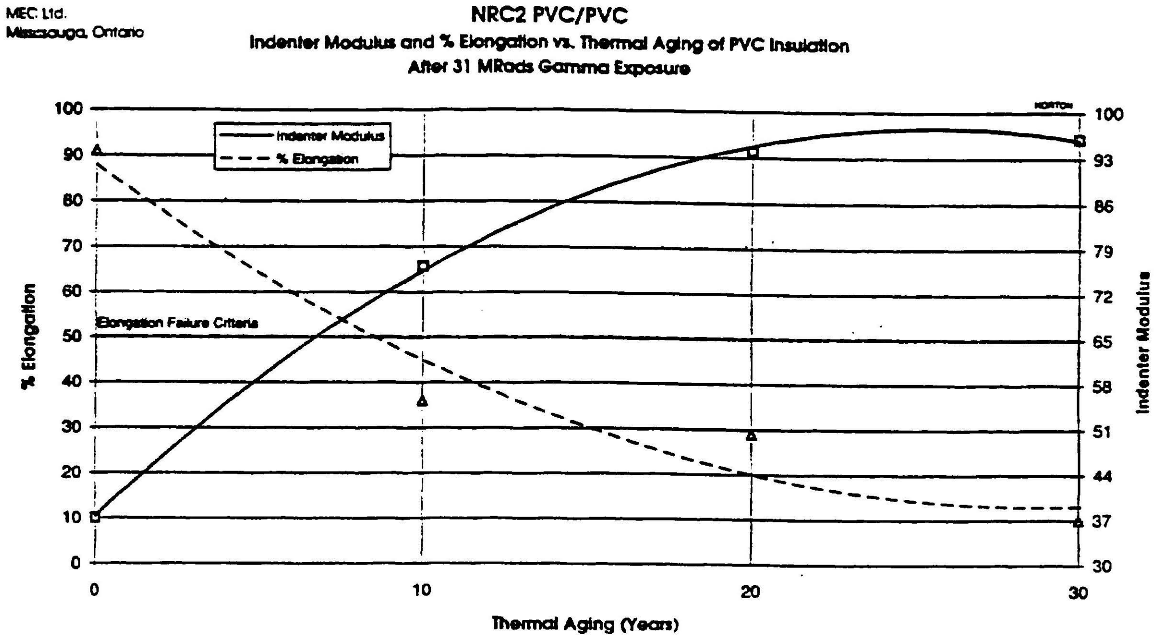

Figure 7

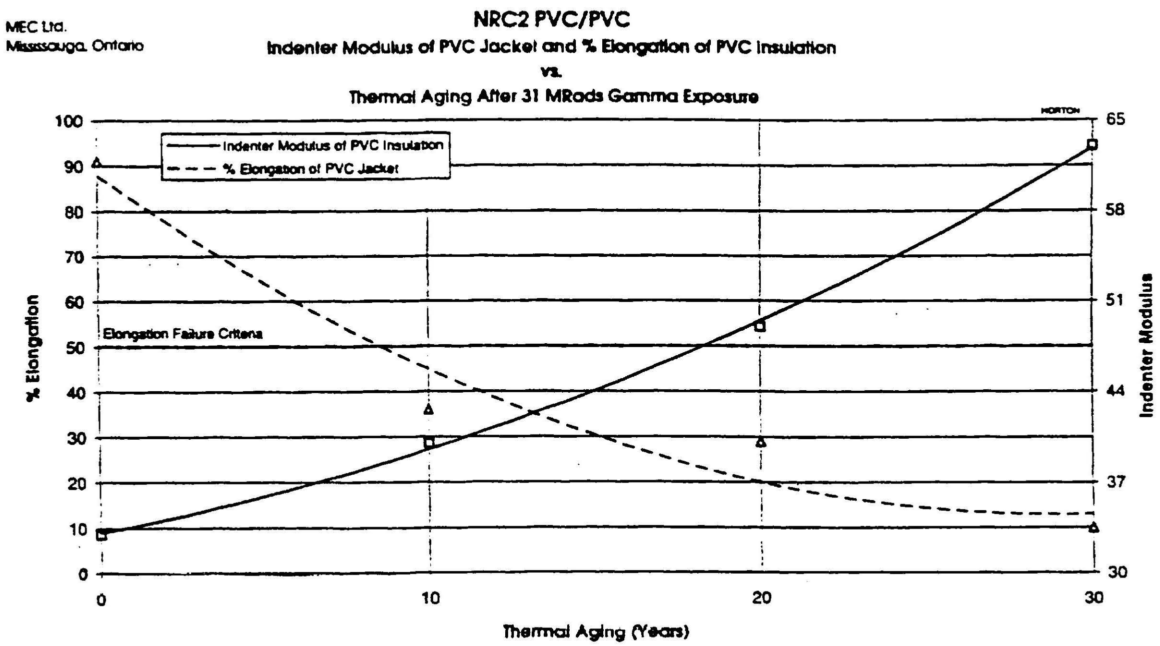

Figure 8